Patent Abstracts of Japan

PUBLICATION NUMBER : 01160841
PUBLICATION DATE : 23-06-89

APPLICATION DATE : 16-12-87
APPLICATION NUMBER : 62316072

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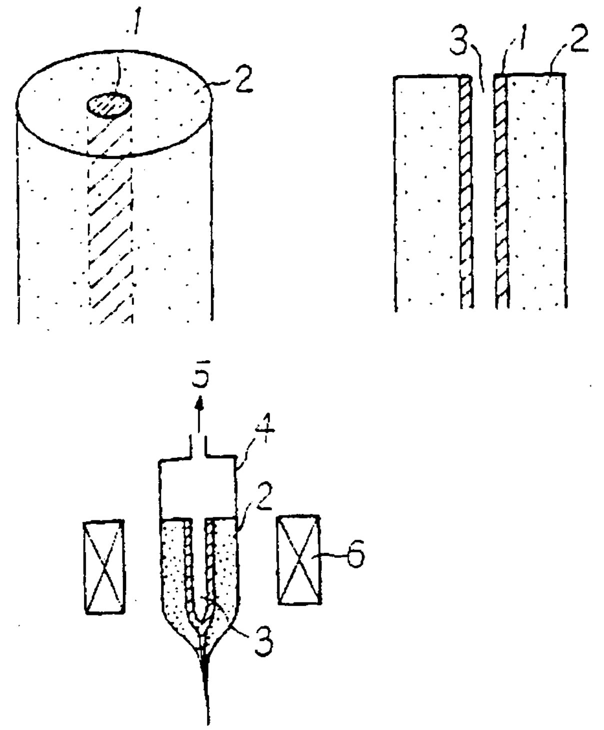
INT.CL. : C03B 37/027 G02B 6/00

TITLE : PRODUCTION OF OPTICAL FIBER



ABSTRACT : PURPOSE: To produce an optical fiber having a large core/clad ratio without eccentricity, by drawing a wire while keeping the interior of a pipelike preform having a hole partially formed in the longitudinal direction in the core under reduced pressure.

CONSTITUTION: A hole 3 passing through the central part of a core part 1 of a preform having the core part 1 and a clad part 2 for an optical fiber is formed in the longitudinal direction so as provide a surface area ratio of the clad part 2 to the core part 1 at a constant ratio of the designed value for the optical fiber using an ultrasonic perforator. The inner surface of the hole 3 is then optically polished or heat-treated in a fluorine gas atmosphere and etched to afford a pipelike preform, which is subsequently set in a drawing furnace 6. One end of the preform is connected through a connecting tool 4 to a vacuum pump 5, heated and drawn in the furnace 6 while decompressing the interior of the preform to 0.1~20Torr.

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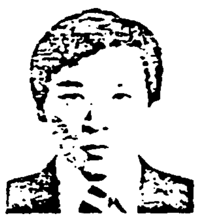
LT-2(1984)Oct.,No.5,New York,USA



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Reduced Pressure Collapsing MCVD Method for Single Polarization Optical Fibers

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p. 634-639

C03B37/018E2

Abstract—A simple fabrication method of single polarization optical fibers has been proposed. Core, clad, and jacket layers are deposited in a silica tube. The tube is then collapsed while the inner pressure of the tube is reduced. The core circularity and the jacket ellipticity are controlled by the careful selection of the softening points of core/clad and jacket materials, and the inner pressure. The pressure reduction and the softening points of the constituent glasses play an important role in fabricating single polarization optical fibers.

I. Introduction

SINGLE-mode fibers that preserve a state of linear polarization over long lengths are required both for use in coherent optical communication systems and in fiber measuring instruments such as optical fiber gyroscopes. The preservation of polarization can be achieved by giving a sufficiently large difference $\Delta\beta$ in propagation constants of two orthogonal HE_{11} modes [1]. To alter $\Delta\beta$ appreciably (say, $\Delta\beta > 2700$ rad/m) [2], it is necessary to introduce noncircularity in the core shape or deliberately enhance the nonsymmetric stress in the core [3].

Propagation characteristics of three single polarization optical fibers, the elliptical-core, elliptical-clad, and elliptical-jacket fibers have been reported [2], [3]. $\Delta\beta$ of 8200 rad/m for elliptical-core fibers and 5200 rad/m for elliptical-clad, elliptical-jacket fibers in the wavelength of 0.633 μm have been observed. However the fabrication method has not yet been discussed in detail.

Manuscript received December 20, 1983; revised April 19, 1984.
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Various fabrication methods of single polarization optical fibers have been proposed so far, such as the grinding method [4] and the rod-in-tube method [5]. Furthermore, the substrate-tube lithography method [6] and the gas-phase etching method [7] have been reported recently. These methods are, however, thought to be more complicated than the conventional fiber fabrication method like the MCVD method. For example, the substrate-tube lithography method requires additional two processes, an exposure of the resist and an etching of the borosilicate layers.

Elliptical-jacket fibers have been fabricated by the rod-in-tube method [8]. In this paper, a more simple fabrication method will be proposed and discussed in detail. The fabrication process comprises the three stages of 1) chemical vapor deposition of the appropriate glassy layers in a silica tube, 2) collapse of the tube and layers into a solid rod composite preform by the use of the reduced pressure collapsing method, and 3) drawing the preform into a fiber. Low-loss elliptical-core, elliptical-clad, and elliptical-jacket fibers can be fabricated reproducibly by this simple method.

II. Reduced Pressure Collapsing Method

A newly proposed fabrication method of single polarization optical fibers, which is called the reduced pressure collapsing (RPC) method is described in this section. In the elliptical-clad fiber, for instance, borosilicate clad and pure silica core layers are deposited in a starting silica tube by using chemical vapor deposition. Then one end of the layered silica tube is heated by an oxyhydrogen burner so that it may be collapsed as shown in Fig. 1. The layered silica tube is mounted between rotating

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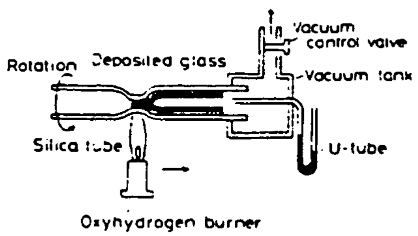

Fig. 1. Apparatus for the reduced pressure collapsing (RPC) method.

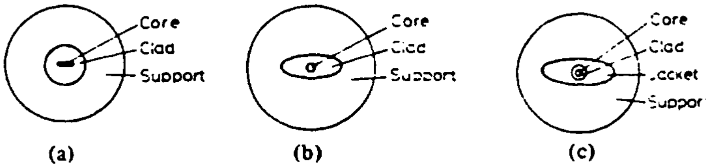

Fig. 2. Cross sections of three single polarization fibers: (a) elliptical-core, (b) elliptical-clad, and (c) elliptical-jacket fibers.

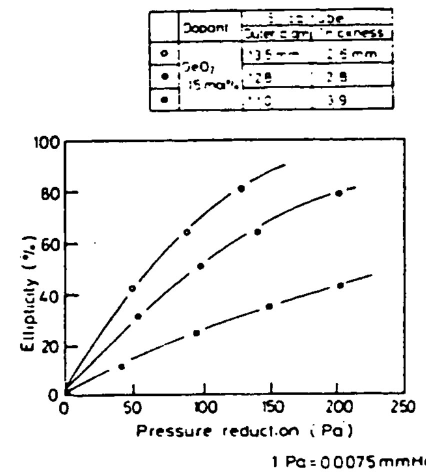

Fig. 3. Relationship between the core ellipticity and the pressure reduction in the elliptical-core fiber for various sizes of starting silica tubes.

chucks on a lathe bed and is always rotating with the constant speed (for example, 50 rpm). The other end of the layered silica tube is connected with the vaccum tank. By adjusting a vacuum control valve in the vacuum tank, the pressure in the tube can be carefully controlled. In case of the fabrication of conventional circular symmetric optical fibers, the inner pressure of the layered silica tube is required to be slightly higher than (or equal to) that of the atmosphere. However, on the contrary, in case of the manufacturing process of single polarization optical fibers, it must be lowered.

The inner pressure is monitored in terms of the difference between water levels of a U-tube whose one open end is inserted in the layered silica tube. At this state, the oxyhydrogen burner is traversed continually (for example, 0.08 mm/s) along the length to make it a solid preform with a circular core and an elliptical clad in the elliptical-clad fiber, for instance. One is apt to think that the preform axis twists along the length. However, the preform cross section is uniform and the preform axis is in a plane over the preform rod in spite of the rotation of the preform during the collapsing. The variations of the ellipticity and the axis of the ellipse are within 5 percent over the preform. Special techniques are not required to keep the preform cross section and the preform axis uniform. The fabrication parameters, however, such as the temperature and the inner pressure should be maintained constant during the collapsing.

In order to obtain a circular preform rod, the traveling speed of the oxyhydrogen burner and the collapsing temperature must be carefully chosen. Those are entirely governed by the inner pressure and the size of the starting tube. The amount of the typical pressure reduction is 10 Pa (~1 mm H_2O) to 200 Pa (~20 mm H_2O), and the collapsing temperature is around 1800°C.

The preform is drawn into fiber with a precision resistance-heating fiber drawing machine. For experimental purpose a fiber length of 1.3 km is normally drawn from a 60-cm preform.

III. Fabrication of Elliptical-Core Fibers

The suitable condition for the fabrication of the elliptical-core fiber is first described. In the elliptical-core fiber shown in Fig. 2(a), the core is always composed of silica glass doped with GeO_2. The propagation constant difference $\Delta\beta$ in this fiber closely relates to the molar concentrations of GeO_2 and the geometrical path difference due to the noncircular core. The pressure reduction plays an important role in making the core elliptical in the elliptical-core fiber.

Fig. 3 shows the relationship between the core ellipticity and the pressure reduction as a function of the size of the starting silica tube. The ellipticity ϵ is defined as

$$\epsilon = (a_x - a_y)/(a_x + a_y) \times 100\ (\%) \qquad (1)$$

where $2a_x$ and $2a_y$ represent major and minor axes of the ellipse, respectively. The core is composed of silica glass doped with 15 mol % GeO_2. The major and minor axes of the elliptical core in the preform rod do not twist, but are in orthogonal planes along the whole length of the preform rod.

It can be seen from the figure that the core ellipticity increases with the pressure reduction. For example, the ellipticity reaches as high as 80 percent in the case of 13.5-mm outer diameter and 2.6-mm thickness of the silica tube. The ellipticity at a given pressure reduction also changes with the size of the starting silica tube. However, from the several experiments, the empirical relation between the core ellipticity and these fabrication parameters has been obtained, which will be given in the next section.

IV. Fabrications of Elliptical-Clad and Elliptical-Jacket Fibers

The elliptical-clad fiber as shown in Fig. 2(b) is composed of the GeO_2 or P_2O_5 doped circular core, the B_2O_3 doped elliptical clad, and the silica circular support. On the other hand, the elliptical-jacket fiber as shown in Fig. 2(c) is composed of four regions: the concentric circular GeO_2 or P_2O_5 doped core and silica clad regions for constructing the low loss waveguide and the B_2O_3 doped elliptical jacket and the silica circular support regions for introducing the large nonsymmetric stress in the core. GeO_2 or P_2O_5 is also doped in the jacket to give the same refractive index as SiO_2 in the support and the clad. This fiber realizes the low loss as well as the good polarization

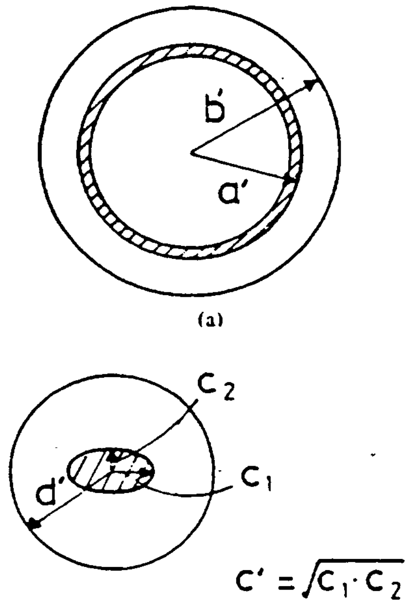

Fig. 4. Cross sections of the layered silica tube before callapsing (a) and the preform after collapsing (b). Parameters a', b', c', d' are so important to fabricate single polarization fibers.

holding [3]. In this section, suitable conditions for the fabrication of the elliptical-jacket fibers at which the jacket is made elliptical as well as the core remains circular is given. This condition is also applicable for the fabrication of the elliptical-clad fiber.

Typical operating conditions are as follows. The raw materials for the deposition process were $SiCl_4$, BBr_3, and $GeCl_4$ for the elliptical jacket, $SiCl_4$ for the circular clad, and $SiCl_4$ and $GeCl_4$ for the core, respectively. All the halides were refined by distillation in advance of deposition to remove the impurities. Concentric elliptical jacket, clad, and core layers were deposited on the inner wall of a starting silica tube by chemical vapor deposition. The size of the starting silica tube is defined by a' inner radius and b' outer radius as are shown in Fig. 4(a). Here, values of a' and b' will be given later. Then the silica tube with concentric deposition layers was collasped while the inner pressure of the tube was controlled as is shown in Fig. 1. The preform rod of radius d' has the elliptical jacket with the major axis c_1 and the minor axis c_2 as are shown in Fig. 4(b).

A. Conditions for Making the Elliptical Jacket

Extensive studies have been made to find the empirical relation between the ellipticity of the jacket and fabrication parameters such as the tube thickness. It was found out experimentally that the jacket ellipticity can be expressed solely by $(b'/a') \times (d'/c')$. Parameters a', b', c', and d' are defined in Fig. 4(a) and (b), where c' is the average radius of the elliptical jacket ($= \sqrt{c_1 c_2}$).

Fig. 5 shows the jacket ellipticity as a function of $(b'/a') \times (d'/c')$ for various sizes of the starting tube. The collapsing condition was such that the temperature was 1800°C, the pressure reduction was 78.4 Pa (8.0 mm H_2O), the traveling speed of the oxyhydrogen burner was 0.08 mm/s, and molar concentrations of B_2O_3 and GeO_2 in the elliptical jacket were

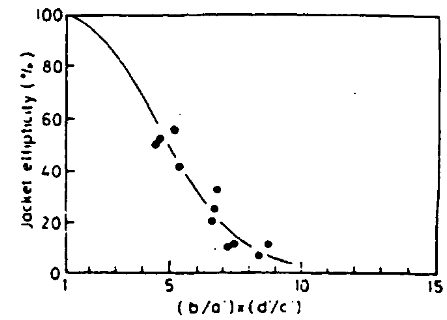

Fig. 5. Relationship between the jacket ellipticity and the tube size before and after collapsing. Solid line indicates the results of (2) and (3) in the text. a', b', c', and d' are given in Fig. 4.

14 and 10 mol %, respectively. It can be seen from Fig. 5 that the ellipticity varies exponentially with $\{(b'/a') \times (d'/c')\}^2$ as is shown by the solid curve for all silica tubes used in these experiments. Therefore, the ellipticity ϵ can be expressed empirically by the following equation

$$\epsilon = 100 \times \exp\{-A(x-1)^2\} \ (\%)$$
$$x = (b'/a') \times (d'/c') \tag{2}$$

where the coefficient A may be a function of the pressure reduction and can be determined later. It is worth mentioning that (2) holds even if the collapsing temperature (1700°C ~ 2000°C) and the traveling speed (0.02 ~ 0.2 mm/s) of the oxyhydrogen burner are varied. Attention must be paid to the fact that (2) includes only the ratio of (b'/a') and (d'/c'), and does not depend on the absolute value of the size of the starting silica tube. Therefore, (2) can be applied to any silica tube.

The reason why the ellipticity varies with $\{(b'/a') \times (d'/c')\}^2$ can be derived qualitatively from the following two facts. First, the relative cross-sectional area of the rigid silica glass increases with both of $(b'/a')^2$ and $(d'/c')^2$. This can be easily understood from Fig. 4. Therefore, the rigidity of the silica tube is thought to increase with the production of $(b'/a')^2$ and $(d'/c')^2$. Second, whether the elliptical deformation occurs or not depends on the rigidity of the silica tube. Consequently, it can be imagined that the ellipticity relates to $\{(b'/a') \times (d'/c')\}^2$.

In order to find out the coefficient A experimentally, the effect of the pressure reduction on the jacket ellipticity has been studied. Fig. 6 illustrates the relationship between the jacket ellipticity ϵ and the pressure reduction P. In these experiments, the parameter of the starting silica tube was $a' = 3.9$ and $b' = 6.6$ mm, and molar concentrations of B_2O_3 and GeO_2 in the elliptical jacket were 14 and 10 mol %, respectively. It can be seen from Fig. 6 that the jacket ellipticity changes monotonically with the pressure reduction like Fig. 3. Therefore, from Fig. 6 and (2), the coefficient A can be determined as follows:

$$A = \frac{3.52}{P}. \tag{3}$$

The solid curve in Fig. 6 is the best fitting curve obtained from (2) and (3).

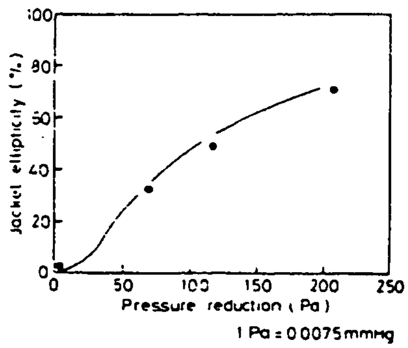

Fig. 6. Relationship between the jacket ellipticity and the pressure reduction for the silica tube with 6.6-mm outer radius, 3.9-mm inner radius, and the B_2O_3 concentration of 14 mol%.

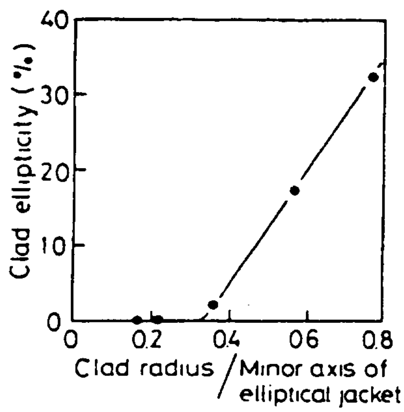

Fig. 7. Relationship between the clad ellipticity, which is equivalent to the core ellipticity, and the clad radius normalized by the minor axis of the elliptical jacket. A starting silica tube before collapsing has the outer radius of 6 mm and the inner radius of 3.4 mm.

From (2) and (3), the preform rod with the elliptical jacket have a jacket ellipticity ϵ can be obtained provided that the pressure reduction P and the silica tube parameters a', b', c', and d' may be set on the basis of (2) and (3).

B. Conditions for Making the Circular Core

In the elliptical-jacket fiber, the jacket must be elliptical, but the core must be circular to minimize the transmission loss due to the structural imperfection. Therefore, we must find the condition by which the core remains circular even in the case that the jacket is made elliptical. In order to lower the transmission loss due to the material absorption in a single-mode operation, it is required that the core and the clad are composed of SiO_2-GeO_2 and SiO_2, respectively, and moreover, the concentration of GeO_2 in the core must be less than 5 mol % [3]. Thus from the material point of view, the core and the clad have similar softening points and expansion coefficients. So that it can be imagined that the core becomes circular only when the clad is made circular. In this section, therefore, only the condition for making the circular clad is given.

From the several experiments, we have found that the clad ellipticity which is equivalent to the core ellipticity strongly depends upon the clad size and the elliptical jacket size. Fig. 7 shows the typical clad ellipticity as a function of the ratio η of the clad radius to the length of the minor axis of the elliptical

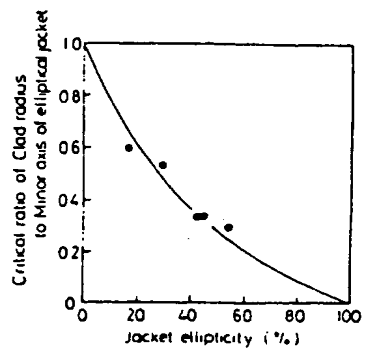

Fig. 8. The critical ratio of the clad radius to the minor axis of the elliptical jacket as a function of the jacket ellipticity.

jacket for 45-percent jacket ellipticity. In these experiments, the following parameters were fixed. The size of the starting silica tube was $a' = 3.4$ mm and $b' = 6.0$ mm, and the thickness of the deposited jacket layer containing 14 mol % B_2O_3 was 390 μm. The layered silica tube was collapsed under a pressure reduction of 98.0 Pa (10.0 mm H_2O). Thus the jacket ellipticity could be fixed to be 45 percent. It is understood from Fig. 7 that the ellipticity of the clad (core) is influenced by $\eta = b/c_2$ where b is the radius of the clad in the preform and the clad becomes circular in the region of $0 < \eta < \eta_c = 0.33$, where η_c is the critical value giving the circular clad.

These experiments have been continued for various jacket ellipticities to obtain η_c. Fig. 8 shows η_c as a function of the jacket ellipticity. From these results, it is found that η_c decreases with the jacket ellipticity and may be expressed by

$$\eta_c = \frac{b}{c_2} = \left[\frac{248}{100 - \epsilon} - 1.48\right]^{-1} \tag{4}$$

where ϵ is the jacket ellipticity. Therefore, if the jacket ellipticity is fixed to be ϵ_c by (4), the clad radius must be satisfied with

$$b \leqq c_2 / \{248/(100 - \epsilon_c) - 1.48\} \tag{5}$$

to give the circular clad (core) at the preform state.

Here, the reason why η_c decreases with the jacket ellipticity as shown by (4) is described. Basically, the clad (core) becomes circular by its own surface tension as described in the next section. However, the larger the jacket ellipticity becomes, the smaller the width of the elliptical jacket region ($= c_2 - b$) becomes. Therefore, the clad is influenced by the support in adddition with its own surface tension. This leads to the deformed clad, so that η_c becomes small as the jacket ellipticity increases.

IV. Discussions

In this section, the mechanism why the concentric circular core and clad, the elliptical jacket and the circular support in the elliptical-jacket fiber can be fabricated by the reduced pressure collapsing method will be discussed briefly.

Since the starting silica tube is relatively thick (say 2-mm thickness), the outer side of the layered silica tube is little influenced by the pressure reduction. Moreover, the temperature gradient is initially higher at the outer side than at the inner side, but the cooling rate at the outer side is much faster than

at the inner side during the collapsing stage. Therefore, the surface tension at the outer side of the silica tube is much stronger than the effect of the pressure reduction. So the circular shape in the outer side is to be maintained after collapsing.

However the inner side is dominated mainly by the pressure reduction so that it is to be flattened. If the heating treatment further continues, the inner side has its temperature so raised that it is liable to be deformed. This is just like a flattened rubber ball from which air is released. Inside of the starting silica tube, the jacket layer (SiO_2-B_2O_3-GeO_2) having a lower softening point, and the clad (SiO_2) and the core (SiO_2-GeO_2) layers having higher softening points have been deposited. Immediately after collapsing, the jacket layer becomes elliptical, but has its viscocity gradually lowered. As a result, the clad and the core are floating in the elliptical jacket having its viscocity lowered. Since, at this time, the clad/core region does not have any effect of the pressure reduction, the clad/core layers are forced to be a circular shape by their surface tensions. Therefore, whether the clad and the core are liable to become circular or not is entirely determined by the careful selection of the softening points and viscosities of glass materials in the elliptical jacket, the ratio between the relative sizes of the elliptical jacket and clad regions, and the pressure reduction.

Here, the reduced pressure collapsing method is summarized. First of all, the condition for making the jacket elliptical is determined by (2) and (3). Next, in order to give the circular core, it is necessary that the clad and the core must be made liable to become stably circular in the softened jacket region during the collapsing stage. For this necessity, it is sufficient that

$$\alpha_1 > \alpha_2 \quad \text{and} \quad \alpha_3 > \alpha_2 \tag{6}$$

where α_1, α_2, and α_3 designate the softening points of the clad (and/or core), jacket and support regions, respectively. In order to satisfy the above conditions, it is desired that the support and the clad (core) are made of SiO_2 and/or SiO_2-GeO_2 (P_2O_5), and that the jacket is made of SiO_2 containing 3 mol % to 30 mol % of B_2O_3 as a dopant. Moreover, it is required from (4) that the ratio of the clad to the jacket radius must be adequately designed.

From the above discussions, it can be concluded that the most important factor to make the jacket elliptical is the amount of the pressure reduction and that the one to make the core circular is the difference of the softening points between glass materials in the clad (core) and the elliptical jacket.

V. Conclusions

Single polarization optical fibers have been fabricated by the reduced pressure collapsing (RPC) method. Core, clad, and jacket layers were deposited in a silica tube. Then the tube was collapsed while the inner pressure of the tube was reduced. The core circularity and the jacket ellipticity were controlled by the careful selection of the softening points of the core/clad and jacket materials and the inner pressure. The pressure reduction and the softening points of the constituent glasses play an important role in fabricating single polarization optical fibers.

Typical elliptical-jacket fiber fabricated by the RPC method has a 6-μm core diameter, core radius/clad radius = 0.5, jacket ellipticity = 55 percent, B_2O_3 concentration = 14 mol %, and a 150-μm fiber diameter. This fiber has less than 1-dB/km transmission loss and less than −30-dB extinction ratio (1-km length) at 1.3-μm wavelength.

Acknowledgment

The authors wish to thank Dr. K. Sato and Dr. M. Kudo of Hitachi Central Research Laboratory and Dr. K. Mikoshiba of Hitachi Cable Ltd. for their helpful suggestions and encouragement and to Dr. H. Kajioka and T. Tokunaga of Hitachi Cable Ltd. for their useful discussions.

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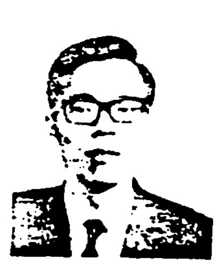
He joined Central Research Laboratory, Hitachi Ltd., in 1974, and has engaged in research on optical-fiber fabrication and characterization.

Dr. Katsuyama is a member of the Institute of Electronics and Communication Engineers of Japan, and the Physical Society of Japan.



Hiroyoshi Matsumura was born in Chiba, Japan, on November 3, 1942. He received the B.Sc. decree from the University of Kobe, Kobe, Japan and the Ph.D. degree from the University of Southampton, Southampton, England.

He joined Nippon Sheet Glass Company in 1967, where he did the research work on the graded index fibers. He was one of the inventors of the SELFOC fiber. From 1972 to 1978, he had a sheet in the University of Southampton and in 1975 he became the Pirelli Reseach Fel-

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LT-2(1984)Oct.,No.5,New York,USA

low in the Department of Electronics, University of Southampton. His main interest was the propagation characteristics of single-mode fibers. In September 1978, he joined the Central Research Laboratory, Hitachi Ltd. From 1978 to 1981, he concentrated in the development of single polarization optical fibers called the Elliptical Jacket Fibers. Since he succeeded in it, his research interests have been in integrated optics and semiconductor lasers.

Dr. Matsumura has been awarded two prizes from IEE in England and one prize from IEE in Japan.

Tsuneo Suganuma was born in Nagano Prefecture, Japan, on December 8, 1941. He received the B.S., M.S. and the Dr. Eng. degrees in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1965, 1967 and 1970, respectively.

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High-Birefringence Optical Fibers by Preform Deformation

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p. 639-641

Abstract—High-birefringence optical fibers have been fabricated using a preform deformation technique in which an initially round preform is locally heated and squeezed from two sides. This technique has been used to make both polarization-preserving and single-polarization fibers. A novel feature of these new fibers is their rectangular shape which facilitates location of the principal axes and increases resistance to polarization breakdown from external perturbations. These fibers have circular cores, low loss, and excellent polarization holding.

I. Introduction

A VARIETY of structures now exist for introducing birefringence to make polarization-preserving optical fibers. Most birefringent fibers introduce differential stress in the core by way of an elliptical stress cladding [1], [2], stress in an elliptical core [3], or isolated stress lobes [4], [5], [6]. Polarization-preserving fibers also utilize geometrical birefringence from a noncircular core [7] or from index side-pits next to the core [8]. These structures are made by a variety of techniques which include grinding flats on the preform before and after deposit and collapse [1], pressure differential during collapse [2], rod and tube techniques [4], or etching [5], [6].

This paper describes a new technique for producing stress-birefringent fibers by preform deformation: colloquially referred to as "preform squashing". In this technique, a circular preform is first fabricated containing the core and a circular highly doped layer which will become the stress cladding. The preform is then locally heated and squeezed from the sides as illustrated in Fig. 1. At the softening temperature of the silica substrate, the highly doped stress layer is sufficiently fluid that it flattens under the pressure. The weakly-doped core remains round. The fiber is then drawn at a temperature low enough to prevent its rounding out in the furnace.

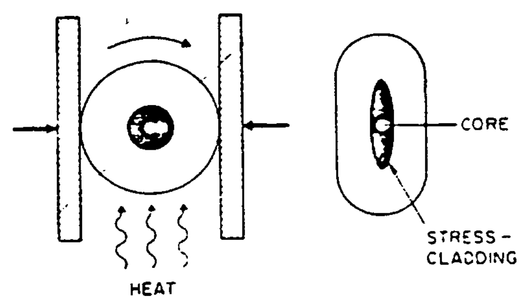

Fig. 1. Deformation of an initially round preform by local heating and squeezing from the sides. The final fiber is rectangular in shape with a highly elliptical stress cladding.

Some examples of structures produced by preform squashing are illustrated in Fig. 2. The first structure (Fig. 2(a)) has a round Ge-doped core with an extremely elliptical stress-cladding. Fig. 2(b) shows a similar fiber with a silica core which requires a large fluorine-doped outer cladding. Fig. 2(c) shows a Ge-doped core, a circular silica barrier layer, and a stress-cladding no wider than the barrier layer. These structures form a link between birefringent fibers using elliptical stress-claddings and those with isolated stress lobes. The extremely elliptical stress-cladding is efficient in its use of stress material to produce high birefringence [9].

The present method has also been employed to make single-polarization fiber [10]. Wide single-polarization bandwidth

Manuscript received February 21, 1984.
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